A STUDY OF THE IMPORTANCE OF WIND ON REINFORCED CONCRETE ARCH BRIDGES

BY
POWELL PAO-WO TSU
B.S.C.E., Chiao-Tung University, 1933
M.C.E., Cornell University, 1935
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Mr. E. E. Brandow, Commonwealth of Pennsylvania, Department of Highways, George Westinghous Bridge.

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I. INTRODUCTION

Within the last ten years, reinforced concrete arch bridges have been built, reaching a single span length of 700 feet or more.[1] Such achievement cannot be accounted for merely by improvements in construction methods, but depends in a large measure also on the confidence of engineers gained through a more comprehensive understanding of structural action, and of the relative importance of various influences such as live load, the effect of temperature, shrinkage, plastic flow, rib shortening, interaction of rib and floor, etc. However, with the exception of one article entitled "Wind Stresses in Reinforced Concrete Arch Bridges,"[2] there is scarcely any mention in engineering literature of the effect of wind on reinforced concrete arch bridges.

Mr. Eremin's study was based on analyzing the arch rib under wind as a curved girder, taking into account as well the effect of bracing struts between ribs. His treatment leads to a reasonable estimate of the effect of wind on through arches, but nevertheless is incomplete in that it does not include the effect of wind on floor and columns of an open spandrel deck arch. In this study the author has included the effect of wind on floor and columns as well as on the ribs of arch bridges and has atempted to evaluate the effect of the stiffness of deck and columns.

The primary purpose of this investigation was to determine whether the effect of wind on reinforced concrete arch bridges is of sufficient importance to require specific inclusion in design, calculations, and additions to the areas of the arch ribs.

An opn spandrel arch bridge under the action of wind is a highly indeterminate structure. Exact analysis would involve the finding of six restraint forces at each column junction with the arch rib, and may,

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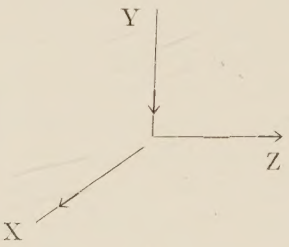
1. The main arch span of Esla Viaduct, a reinforced concrete railway bridge over the River Esla in Spain, has a span length of 672 feet.

2. It is an article written by Mr. A. A. Eremin, Associate Member of American Society of Civil Engineers, that appeared in the Transactions of the American Society of Civil Engineers, Vol. 102, 1937.

in fact be impossible because of uncertainty regarding the torsional stiffness of deck consisting of slabs and stringers. In order to obtain a fairly satisfactory estimate of the effect of wind with a practicable expenditure of time and labor, it was assumed that the wind acts symmetrically without impact on a symmetrical structure: the deck first being assumed as equal to the stringer thickness and then to the slab thickness. Also to study the six restraints simultaneously was found to be impracticable; to approach the solution systematically by first considering the most important restraints, and then successively studying the less important effects in turn seemed to be the best procedure as by so doing, the structural action can be more clearly visualized, and the possible effect of the less significant restraints upon the structure and the significant restraints better grasped.

In the discussion which follows, all references to coordinate axis will be in accordance with the definition in Fig. 1.



With this end in view, the significant restraints, the shear in the X direction and the vertical stress in the Y direction, were first studied considering the actual structure as having ball and socket connections at each column junction with the arch rib, provision being made for the sliding of column bases in the Z direction. The structure was statically determinate by cutting loose all the column bases except those at the springings. Under this condition, when wind acts on the floor alone, each column at the springing will deflect horizontally under a shear of one quarter of the wind load by virtue of the symmetry of loading on a symmetrical structure and on account of the fact that the moment of inertia of deck about the Z axis is very much greater than the moment of inertia of columns about the Z axis. The deck likewise deflects horizontally as a simple beam under the uniform wind load. Thus, the intermediate columns deflect, normal to the plane of the arch rib, by

amounts equal to the sum of the deflection of the springing column and those due to bending of the deck at the points of the floor to which these columns are attached. For wind acting on the columns, additional deflections due to bending of the columns themselves and the twisting of the deck should be added, while for wind acting on the arch rib, the intermediate column bases remain stationary, only the rib itself deflecting as a curved girder. These deflections represent the departures from continuity in the X direction. In order to preserve the continuity, it is necessary to pull the column bases and the arch rib together by applying pairs of unit horizontal force in the X direction to each. The horizontal shears in the X direction existing at each column junction are obtained by solving a set of simultaneous equations involving those elastic constants that represent the deflections in the X direction when pairs of unit horizontal force are applied to various intermediate column bases and to the corresponding points on the arch rib.

It is to be understood that while the structure is made to preserve continuity in the X direction, the arch ribs are kept at their original vertical positions by holding forces at each column joint. By statics, the magnitudes of these holding forces at each column joint are equal to twice the X shears at these joints times their respective column heights and divided by the distance between columns in the X direction. These holding forces have to be removed as they are not there in reality. In removing these holding forces, the deck will be subjected to torsion at each column joint, producing horizontal and vertical deflections. In the meantime, the arch rib likewise deflects in the vertical direction. This vertical discontinuity has to be eliminated. In doing so, a separate set of elastic constants, representing the vertical deflections at various intermediate columns due to the application of pairs of unit vertical loads to the column bases and to the arch rib at the corresponding points, is needed, to permit another set of simultaneous equations involving the unknown vertical stresses in the Y direction at various column base joints. There are, of course, horizontal deflections at the various column base joints due to the application of pairs of unit vertical force. They are made use of in applying the subsequent horizontal shear corrections because the horizontal deflections as a result of the establishment of vertical continuity may not be exactly equal to those after the removal of the holding forces. In making the horizontal shear corrections, application of holding forces is again assumed. Thus, the cycle repeats

itself until eventually the corrections are so small that further corrections are unnecessary. This process may be called the method of successive corrections.

Having found the two restraints at each column base junction, the problem reduces to an analysis of the arch rib as a curved girder for the maximum bending stress about the Y axis and the torsional shearing stress due to the wind and the restraint forces acting on the arch rib.

Study of the less significant restraints follows closely the same procedure of analysis. In all cases, departures from continuity are first ascertained, elastic constants found and then unknowns found from a set of simultaneous equations. The introduction of a new restraint would upset the equilibrihm of restraints previously reached. So corrections are necessary to restore them from disturbance and these corrertions in turn bring in disturbances to the equilibrium of new restraints. The more restraints are added, the more processes of corrections are required. It is evident then that unless the more significant restraints are first studied and the other restraints have small effect upon the significant restraints, this process of analysis by adding one restraint after another is also laborious. In the case of wind load, however, this procedure serves very well because the horizontal shear in the X direction happens to be the only restraint that is of significance. The horizontal shear in the Z direction and the moment about the X axis, acting at each intermediate column base junction, are insignificant in magnitude because of the small shearing and bending stiffness of the columns and also the small vertical stresses in the Y direction in columns due to the small torsional rigidity of the deck. The other two restraints, the torque about the Y axis and the moment about the Z axis, are likely also small by virtue of the small torsional and bending stiffness of the columns. Besides, these two latter restraints help reduce the maximum bending moment at the springing due to the wind and the horizontal shearing forces in the X direction acting on the arch rib.

For the arch bridges provided with expansion joints in the deck at or near springing columns, the procedure of analysis does not materially differ from the case of a continuous deck. The only difference lies in the fact that since the columns now all rest on the deformable rib, the elastic constants will in this case involve the elasticity of the arch rib in addition to those already enumerated.

II. SUMMARY

Arch action of the rib resulting from the wind acting on the entire structure is negligibly small. As far as the curved girder action is concerned, the horizontal shears in the X direction seems to be the most significant restraining force. The other two restraints, the moment about the Y axis and the torque about the Z axis, acting on the arch rib, tend to lessen the maximum bending moment about the Y axis at the springing.

Analysis of an arch rib as a curved girder under wind load without considering the stiffness of deck is on the safe side provided the deck is continuous. The amount of reduction of the maximum bending moment about the Y axis at the springing due to the restraint of deck is uncertain because of the uncertainty of the torsional rigidity of deck. In the case of a deck provided with expansion joints near the springing columns, the analysis without considering the superstructure results in some error on the unsafe side.

Of the two arch bridges analyzed, one being the George Westinghouse Arch Bridge with a span of 460 feet and the other being a 150 feet span bridge from the Alsea Bay Continuous Arch System, it was found that the fiber stress on the arch rib due to the bending about the Y axis was but one-fifth of the dead load stress if the deck is continuous and one-third of the dead load stress if the deck is provided with expansion joints near the springing columns and at the quarter points of the span. Both of these cases were calculated under the assumption that the column base joints are ideally ball and socket connected. Actually these ratios would be smaller because of the effect of the other two restraining forces, namely the moment about the Y axis and the torque about the Z axis acting on the arch rib. It seems reasonable to conclude therefore that the effect of wind on reinforced concrete arches cannot be sufficiently important to justify inclusion in design, in bridges of proportions comparable to those studied.

VITA

Powell P. W. Tsu was born in Shanghai, China, September 8, 1914. He graduated from Soochow Middle School in 1929. In June 1933, he graduated from Chiao-Tung University, formerly known as Nanyang University, with the degree of Bachelor of Science in Civil Engineering.

Following groduation, he was awarded a graduate scholarship for advanced study abroad by the Kiangsu Provincial Government.

He first registered in the Graduate School of Cornell University, major in Structural Engineering and minor in Hydraulic Engineering. In Summer 1935, he completed all the requirements leading to the degree of Master of Civil Engineering.

In September 1935, he enrolled for additional study at the Engineering Graduate School of Harvard University. There he specialized in the field of Soil Mechanics and Foundation under the supervision of Professor Arthur Casagrande. In June, 1937, he graduated with the degree of Master of Science.

He came to the University of Illinois in the fall of 1937 and has carried on work in the graduate school since that time.